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Citation for the original published paper (version of record):

Gosens, J., Hellsmark, H., Kåberger, T. et al (2018). The limits of academic entrepreneurship: Conflicting expectations about commercialization and innovation in China's nascent sector for advanced bio-energy technologies. *Energy Research and Social Science*, 37: 1-11. <http://dx.doi.org/10.1016/j.erss.2017.09.014>

N.B. When citing this work, cite the original published paper.



The limits of academic entrepreneurship: Conflicting expectations about commercialization and innovation in China's nascent sector for advanced bio-energy technologies

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ARTICLE INFO

Keywords:

Academic entrepreneurship

China

Bioenergy

Third mission

Technology transfer and commercialization

ABSTRACT

Despite many years of substantial government research funding, advanced bio-energy technologies in China have seen limited commercial application. Chinese policy makers are increasingly critical of academic organizations for neglecting their role in the transfer of scientific results into industrial applications. We interviewed a selection of Chinese research groups working on bio-energy technologies, and asked them to describe their efforts at commercialization. We found that they focus their research on technological pathways with commercial potential, they patent and attempt to license their technologies, they are highly involved in large scale demonstration plants, and have created a number of new firms. Industry and government may have unrealistic expectations on the maturity and scale of technologies that academia can develop, however. These findings contrast with many earlier analyses of early commercialization stages of novel technologies, which have commonly identified lacking academic entrepreneurship as a root cause in stalling development.

1. Introduction

Decades of rapid economic development have increased Chinese carbon dioxide to the point where these are now the world's largest [1]. Power generation, heavy industry and transport also contribute to severe levels of local air pollution in China's urban centres [2]. Concurrently, the industries that have previously buoyed economic development (export oriented, labour intensive manufacturing and heavy industries) are losing traction as a successful and desirable mode of economic growth.

Chinese policy makers are pushing for two interrelated transformations to deal with these issues. First, China has ambitious plans for renewable energy, aiming for 15 per cent by 2020 [3]. Second, policy makers are pushing for economic restructuring, moving away from energy and resource intensive industries, and towards innovation driven growth [4]. Particular attention is given to seven 'strategic emerging industries', which include environmental protection, clean transportation, and renewable energy [5]. The R&I policy targets

include, amongst others, (1) a substantial increase in R&D intensity (from 1.75% of GDP in 2010 to 2.5% by 2020), (2) improving indigenous innovative strength, and the absorptive capacity for foreign technology, and (3) improved levels of technology transfer, i.e., the application of scientific results from universities and research institutes in commercial, industrial applications, in particular in high-tech industries [4].

The first two goals should help in creating 'world-class research institutions' [6], whilst the latter goal targets what has been called the universities' 'third mission' [7]. This third mission 'encompasses all activities related to the generation, transfer, use, and exploitation of knowledge and other capabilities developed inside universities where the ultimate application is in non-academic environments' [8; p208], whereas the first and second missions refer to educational and research tasks [8,9].

With regard to renewable energy sectors, there have been an increasing number of reports that have highlighted Chinese accomplishments in recent years. Despite marginal developments until circa 2005,

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<http://dx.doi.org/10.1016/j.erss.2017.09.014>

Received 15 May 2017; Received in revised form 2 September 2017; Accepted 8 September 2017

Available online 19 September 2017

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Chinese investments and installations of renewable power have been the largest globally in recent years [10,11]. Furthermore, Chinese firms are increasingly dominant in equipment manufacturing [12,13], as well as in RD & D output for renewable energies [14,15]. Chinese achievements, however, are particularly apparent in wind and PV sectors [10,11,14,15]. China's bio-energy sector has remained behind in development, compared with global averages, compared with successes in its wind and PV sectors, and even compared with the relatively modest Chinese development targets for bio-energy [16–19]. This is in spite of an abundance of biomass resources, and substantial research efforts into a wide variety of bio-energy pathways [20–25].

As has been the case in other countries [26], Chinese policy makers have voiced criticism on the 'return on investment' generated from science spending, in particular in terms of commercialization results [27,28]. The issue has been a focal point in recent discussions on reform of the Chinese Academy of Sciences, China's biggest science organization [28]. This raises the question whether or not the stalling development of China's bio-energy sector is due to lacking academic entrepreneurship, i.e., whether or not academics are doing too little to have their R & D products developed into industrial applications.

This paper presents a case-study of academic entrepreneurship in China's emergent innovation system for modern bio-energy technologies. Academia are understood to personnel at universities as well as research institutes throughout this paper. We analyse (1) what efforts Chinese academia pursue in commercializing the products of their R & D on bio-energy technologies; (2) whether or not this has been a key barrier in the development of the sector; and (3) what other innovation system weaknesses are limiting the transfer and development of academic R & D products into subsequent economic activity.

2. Theory and method

Policy makers across the globe have at occasions voiced criticism at the, in their eyes, limited societally useful returns from substantial research funding. Some have called for the addition of a 'third mission' to university strategy, for integrated attention to commercial development, or otherwise societally useful application of university research. This 'third mission' is in addition to the existing missions of education and basic research [29]. This policy agenda was inspired by earlier successful examples of university-industry collaboration at e.g., Stanford and MIT in the 1930s, but expanded throughout Northern Americas and Europe in the 1980s and 1990s [29]. A number of universities has reported significant revenues from business start-ups and licensing of patents [30].

In spite of successful examples, however, there is a rather voluminous body of literature that is more critical of academic entrepreneurship and its role in emergent technological fields. The criticism remains that academia have a too myopic focus on fundamental research. They have less regard for development phases beyond scientific or technical breakthroughs, nor are their research agendas strongly driven by industry needs [31].

Some have pointed out that this is in fact partially due to government administered research funds, which are usually mandated only to fund more fundamental forms of research [31,32]. This is out of concern that governments are not particularly good at 'picking winning technologies', and that such choices would create unequal, sub-optimal, market competition between technological alternatives [33,34]. Further, academic rewards, including future career opportunities, are also skewed towards the more fundamental phases of knowledge development [32,35].

There are also institutional or cultural frictions surrounding this third mission. Studies by Kirby [35] and Williams [36] found that university management and staff opposed placing an emphasis on entrepreneurialism, out of fear it would erode core academic values, "such as intellectual integrity, critical inquiry and commitment to learning and understanding" [36; p19]. Courses in entrepreneurship in higher

education curricula have generally been limited to business administration programs, prompting organizations including the US' National Academy of Sciences and the European Commission to call for their expansion into technical and scientific programs [30]. Other analysts have commented that university faculty not only lack the motivation and inclination, but also the talent to develop more entrepreneurial activities [35,37].

As our empirical focus is on emergent innovation systems in China, we should consider the specifics of an emerging economy environment on academia's third mission. Policy makers in China and other emerging economies in Asia have pushed for a more direct involvement of universities in industrial innovation. Domestic universities are considered as critical agents in developing indigenous innovative capacity, and as a conduit for understanding and utilizing advanced foreign technology in domestic industries [8,38,39].

So far, there is mixed evidence on the success of this policy push. Some analysts argue that weak R & D capacity in domestic industry has meant that Chinese firms have actively sought collaboration with domestic universities [8,40], whilst others contend that Chinese firms consider domestic universities as having weak innovative capacity, and have therefore chosen to develop in-house R & D efforts [39,41]. Although China has a number of particularly successful examples of university-affiliated enterprises (e.g., Lenovo, Founder), a number of analysts contend that the development of such firms has declined since the mid-2000s [8,39,42]. Lastly, whilst some point to rapidly increased university based patenting in China as indicative of a greater role in the commercialization of technologies, others point out that the share of patents licensed or sold has declined at equally remarkable rates, from 36% of patents granted in 2000 to 8.7% by 2007 [8,43,44].

In the research presented here, we define academic entrepreneurship by building on the framework of 'Technological Innovation Systems' (TIS). This framework suggests a list of activities required to develop or sustain a well-functioning innovation system [45,46] (see Table 1). The framework further stresses that a wide variety of actors is involved in the process, including universities and research institutes, (manufacturing) industry, and government agencies, but also financiers, consultants, certification bodies, maintenance industries, societal pressure groups, consumers etc. [47–49]. This matters because the activities deployed by academics, and the resulting success in furthering the development of the technological field, can never be understood in isolation. The involvement of other actors, and their activities, can create an environment that either limits or propels the results from academic activities into a next phase of technological development. As such, we investigate the extent to which Chinese academia are involved, unilaterally or in cooperation with industry actors, in activities listed under 'entrepreneurial experimentation' in Table 1. That is;

- Creation of new products, processes and services;
- Patenting and licensing of novel technologies;
- Performing of pilot and (commercial) demonstration activities;
- Establishing new firms and production facilities.

This is comparable with items considered in earlier definitions of academic entrepreneurship, but with more explicit attention to piloting and demonstration activities [50–52].

2.1. Method and data collection

We performed a case-study of entrepreneurial activities of academia in China's bio-energy sector. Data collection occurred through a literature review, a round of interviews and a series of workshops. The literature review provided a general overview of the development of China's bio-energy sector and innovation policies. The review also helped identify central actors in academia, industry and policy circles.

A total of 30 specialists were interviewed. Most interviewees were involved in either fundamental or engineering research, and were

Table 1
Innovation system functions and corresponding actor activities.
Source: combination and elaboration on [45,46,48,53].

System function	Requires actors to...
1. Knowledge development	<ul style="list-style-type: none"> • Perform fundamental, proof of principle, prototype R & D activities • Develop instruments, research and engineering design and methods • Perform scientific publishing
2. Knowledge diffusion through networks	<ul style="list-style-type: none"> • Create and participate in cross-disciplinary and cross-sectoral networks • Exchange and combine new knowledge from different fields and backgrounds
3. Influence on the direction of search	<ul style="list-style-type: none"> • Steer technological development, e.g., user-producer feedback, technological roadmaps or preferential policy and regulation
4. Entrepreneurial experimentation and materialization	<ul style="list-style-type: none"> • Develop and articulate visions on the future potential of the technology • Create new products, processes and services • Patent and license novel technologies • Perform pilot and (commercial) demonstration activities • Establish new firms and production facilities
5. Market formation	<ul style="list-style-type: none"> • Identify, utilize and strengthen niche markets • Articulate demand, e.g., by (governmental) launching customers, with consumption quota or policy targets
6. Resource mobilization	<ul style="list-style-type: none"> • Create price premiums, e.g., with eco-branding or with fiscal instruments (taxation or tax exemption, subsidies) • Develop/attract human resources (includes education) • Provide/attract funding, for RD & D and manufacturing facilities • Provide/attract complementary products, services, infrastructure
7. Legitimation	<ul style="list-style-type: none"> • Articulate societal benefits and develop societal acceptance of the novel technology, e.g., by participation in public debate • Lobby for/implement preferential policy and regulations

senior researchers that had been involved in their respective fields for a number of decades. Together, they represent a wide range of different feedstocks used, different conversion processes, and different energy products (see Appendix A). Interview questions were structured using the list of activities presented in Table 1, and focused on the main challenges in the development of the specific technology that the interviewee was working on, and the activities the interviewee undertook to address these challenges.

Interviews were conducted in English, but a Chinese translator made occasional clarifications regarding the content of the questions and answers. Each interview was recorded and notes were taken. Each recording was checked against the notes, and the Chinese translator also made additional clarifications concerning names of places, etc.

In addition, four small seminars were held at Zhejiang University, China Agricultural University, Guangzhou Institute of Energy Technology and Tsinghua University. Two further, larger workshops were organized in Sweden and China, and were attended by representatives of the National Development and Reform Committee, Ministry of Agriculture, Ministry of Technology and the National Energy Administration as well as university and industry representatives.

3. Results: entrepreneurial activities of Chinese academia in the field of advanced bio-energy technologies

In Sections 3.1 through 3.4, we describe activities at commercialization of bio-energy technologies by the interviewed research groups.

3.1. Creation of new products, processes and services

When asked about most recent progress and development issues, many of the researchers' comments immediately coupled current research activities with later, more applied phases of the technology. Specifically, in much of the research on conversion processes, there was a very explicit focus on improving economic competitiveness, e.g., reduction of processing cost or improved conversion efficiency.

For example, one of the research groups at the Guangzhou Institute of Energy Conversion works on cellulosic ethanol production. The group is well aware of the enzymes available from different global and domestic suppliers, their cost and conversion efficiency, and is working on in-house production of enzymes, with the stated purpose of reducing ethanol production cost:

“the quality and effectiveness of different enzymes is different. The highest quality is from Novozymes, but it is too expensive. So in our research we use domestic enzymes, and we also do research to produce our own enzymes. [...] If we have our own enzyme we can lower the [ethanol production] cost.”

Similarly, at a research group at the East China University of Science and Technology, also working on production processes for cellulosic bio-ethanol, using dilute-acid hydrolysis. Central to their work is the improvement of overall processing cost and revenue in a future demonstration plant or production facility:

“Enzymatic hydrolysis is expensive because of the enzymes, and maybe we cannot reduce the cost so much. Because the enzymes are so expensive, we use acid hydrolysis. The problem of this pre-treatment step is the higher energy consumption.” [...] “we are trying to cover energy consumption using gasification of sawdust, which also yields active carbon. This may become quite profitable because the profit of active carbon is about 1000 RMB per ton. [...] Because gasification, I think, also requires a large investment, maybe we will just use combustion in a demonstration plant.”

A number of researchers indicated that even the selection of specific technological pathways to focus on in their research groups were subject to its' market potential.

For example, at the biomass thermal-chemical conversion laboratory at the Guangzhou Institute of Energy Conversion, they realized that their biomass gasification technologies were increasingly being out-competed by direct combustion technologies in applications for electric power production (more on this in Section 3.4):

“Because we cannot get money from power generation, we changed our research to biomass to liquids. [...] So we use gasification and produce syngas and then use syngas to synthesize some liquid fuels.”

Another example of such reorientation was found in the research done at the Biomass Synthesis fuels and Chemicals Lab, also at the Guangzhou Institute of Energy Conversion. This lab had searched for uses of their catalytic biomass conversion technologies, and had identified bio-jet fuels as having strong potential for profitable applications, most importantly because revenue per ton of fuel would be higher for jet fuels than for other transport fuels. The group managed to keep production cost at reasonable levels, and batches of their fuel met international aviation fuel standards, but use of the fuel at commercial

scale remained difficult because of strict aviation fuel regulations. Because of this, the group decided to focus their future research and demonstration activities on the production of bio-gasoline (a hydrocarbon chemically similar to fossil gasoline, not an alcohol fuel). The groups' leader indicated that they were convinced to switch to this product after receiving much interest from industry, amongst others because the chemical similarity means the bio-gasoline is a drop-in replacement and may be mixed at any ratio with fossil based gasoline.

Nearly all of the interviewees indicated that their groups had been providing services, in the form of consulting assignments for industry or government agencies.

In one example, a group of researchers at National Key Laboratory of Biochemical Engineering, Chinese Academy of Sciences, were contracted by a company that had been producing butanol from corn. Production was halted because of a government moratorium on the use of grain for the production of fuel or chemicals. The group consulted the firm about a number of technological options and assisted in the setup of a new production line for butanol and paper produced from corn straw.

Driven by the same government moratorium, a group of researchers at the Guangzhou Institute of Energy Conversion were contracted to help redesign a facility producing ethanol from corn into one that could produce ethanol from feedstocks such as cassava, sweet sorghum and cellulosic material.

There are a number of ways in which the research groups were providing services to government agencies. A small number was recruited as board members in government agencies such as the provincial development and reform commission or department of science and technology. It is further common practice in China to have policy drafts disseminated for comments by experts, and many interviewees indicated they participated in such commenting rounds. Further, a number of interviewees had been invited to participate in drafting regulation. Lastly, an interviewee from the China Agricultural University indicated he had been recruited to collect data and produce an overview paper on the developments of cellulosic ethanol research in universities and research institutes. The assignment does not include basic research, but rather is aimed at providing policy makers with the information needed to draft policy for the further development of the sector.

The results from our interviews, which indicate a relatively high level of interaction with industry, contrast somewhat with national level statistics on the topic. Although the total value of contract research has strongly increased in China over the past decade, universities and research institutes have been receiving a steadily decreasing share of this source of funding (Fig. 1).

The recent debate in Chinese policy making circles, which calls for more attention to commercialization of basic research, is not very

strongly reflected in recent developments in research funding. Rather, experimental development and applied research have always received the bulk of national R & D expenditure, at about 94% in 2002–2004 to about 95.5% of total expenditure in 2009–2011 (Fig. 2). As such, there is relatively little room to further emphasize applied research, at the cost of basic research funding.

3.2. Patenting and licensing of novel technologies

The engineering oriented research groups within our set of interviewees all had a patent portfolio, of between circa ten to several dozen patents, registered with the Chinese patenting office (SIPO). Note that these were the numbers quoted at the research group level, not the institute level. Interviewees mentioned a number of drivers for their relatively high patenting activity.

First, they indicated that it would protect their inventions and, when licensed or sold, had the potential to generate profit for the institute as well as personal bonuses for the research groups' personnel. At all of the groups that we visited, ownership of the patents was held by the institute, although the scientific staff was mentioned as inventor on the patents. Because of the institutes' ownership, decisions on licensing and sales of patent rights were dependent on approval by the institutes' leadership. The suggested distribution of revenue was similar across a number of institutes. Generally, the institute would receive 60% of proceeds. The remaining 40% would be distributed across the research groups' scientific personnel, as personal bonuses, with approximately half (20% of total revenue) going to the research group leader.

Secondly, patent numbers were relatively high because the application process is relatively easy and inexpensive. China has three categories of patents; invention, utility model and design. Invention patents are the most thoroughly examined for novelty and generally take around two to two and a half years to be granted; utility model patents only take about half a year to be granted. It has to be noted that Chinese IPR law has been amended in 2009. Amongst others, novelty demands have been increased to novelty on a global level, whereas this used to be novelty amongst patents file in China only [57]. It was not made clear in our interviews whether researcher were speaking of past experiences in ease of filing patents and whether this amendment had changed this much. Patent application cost, excluding fees for lawyers that help file the application, were stated to be about 1.000–2.000 RMB (about \$150–300), although costs increase depending on the period of protection applied for. These costs would be covered by project funding or by the institute.

Thirdly, patent numbers are used in evaluation of projects, by governmental financing agencies, and in evaluation of personnel, for instance in applications for professorship, by universities and institutes.

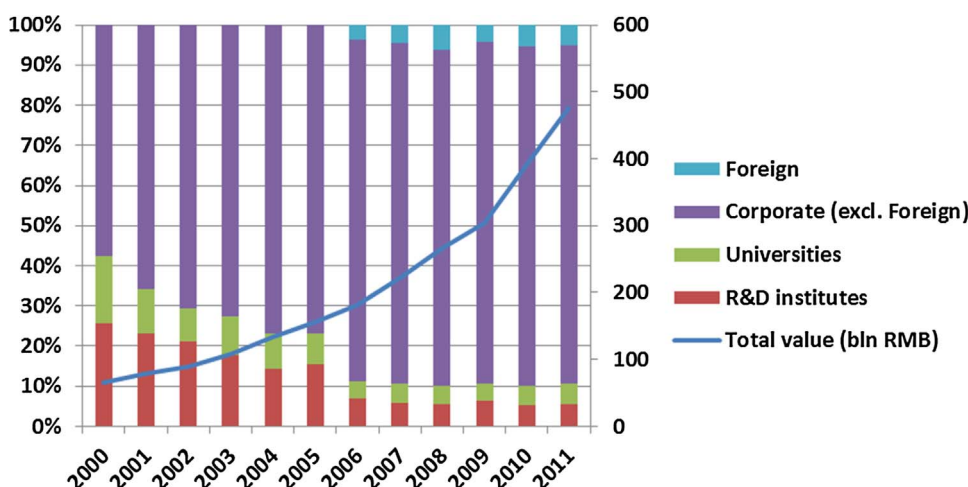


Fig. 1. Research contract value and recipients. Note: total value (in billion RMB) is indicated on the right hand axis. Data prior to 2006 did not specify corporate recipient into domestic versus foreign entities. Contractors included governmental agencies, other public organisations, and corporate organizations. Source: [54,55]

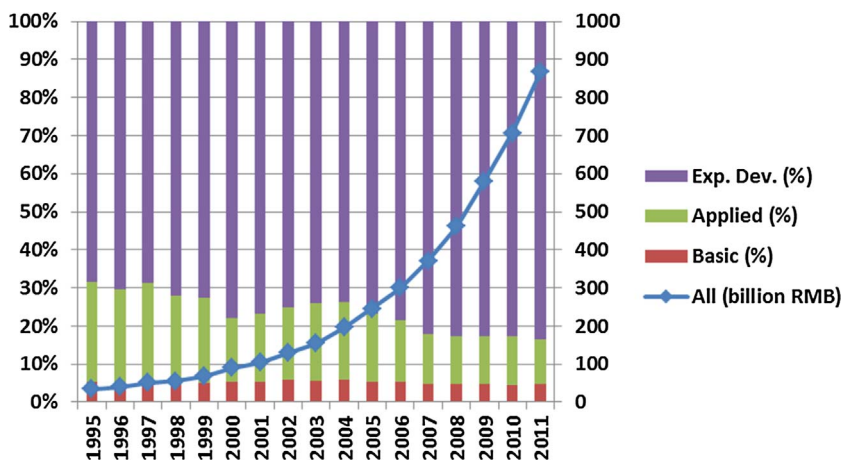


Fig. 2. National R & D expenditure. Note: total value (in billion RMB) is indicated on the right hand axis.

Source: [56]

Multiple interviewees indicated that the criteria in evaluation amounted to perverse incentives to patent. When asked about the drivers for patenting, one of the more forward interviewee's response was as follows:

"Government requirement!" [and only when asked to elaborate:] "It is a requirement included in the contract. When you get this funding, you have to apply for [this number of] patents. Evaluation also includes [whether] we built the equipment or the demonstration plant."

Others commented similarly:

"Frankly speaking, I think that in some universities, maybe half of the patents are just useless; it's just for the promotion, but some are very useful".

And in another interview:

"When the project is finished, after 3 or 4 years, you should have several patents. This is the rule [the project contract stipulated]. So I think half of the patents is garbage'. After several years the owner of the patent will give it up [i.e., cease to pay fees for upkeep], because they think the patent is not useful".

Not all comments were as critical, however. The majority of interviewees indicated they did see patenting as a valuable instrument to protect inventions. One interviewee further stressed that their patenting strategy was more cautious than at most research groups; they rather postponed applications to allow for further testing and experimentation, and ensure the patent would be worth the future upkeep fees.

Only limited success was reported in the licensing or sale of these patents, however. Many of the research groups were involved in a number of relatively large demonstration plant activities (more in Section 3.3), utilizing proprietary technology developed by the research groups. Outside of these activities, however, only two of the interviewees indicated that technologies had made their way into the marketplace through repetitive licensing to an equipment manufacturer or operators of energy or fuel production facilities.

For example, the Institute for Thermal Power Engineering at Zhejiang University was the primary research group involved in China's first domestically developed, commercial scale, biomass power generation technology. Their design for a 12 MW circulating fluidized bed (CFB), direct combustion biomass boiler, was first used in the Sugian power station, which started producing power in 2009 with two of the 12 MW boilers. This design was scaled up to 15, 18 and 20 MW versions, and later the same research group developed a second generation of the boiler, with a 50 MW unit capacity. By 2015, the technology has been employed in 32 power stations across China, operated by several different power companies. In the earliest projects, the research group was strongly involved, providing technical support and helping oversee the construction process. In recent years, the involvement has become

less. The technology is licensed to a boiler manufacturer, which is also responsible for the advertisement and business development of the technology.

At the Institute for Thermal Power Engineering at Zhejiang University, researchers have a long-running research program for the provision of modern biomass technologies in rural settings. In the early 2000s, they developed gasification devices to produce gas for cooking, utilizing crop wastes. The research group has designed and piloted village level scale devices, for approximately 100–150 households, as well as a device for a single household. The devices were taken in production and marketed by an equipment manufacturer under a licensing agreement. Only few units were sold, however. The manufacturer found a niche market in on-site power generation at remote locations, in Vietnam's forestry industry. The technology did not become successful in its target market as poor rural households were not easily convinced to spend money on either a gasification device or cooking gas from a local gas network, when burning fuel wood or crop wastes remained a less costly alternative.

These findings on patenting and licensing largely match with national statistics. China's IP magazine reported several 10,000 s of patents filed by Chinese research institutes and universities, but only several 100 s being licensed to third parties (Table 2). This was true even though the bulk of applications were of the 'invention' category, which are more rigorously examined, and considered to be more valuable. Note that these numbers refer to all patents, not just those in the bio-energy domain. Although government requirements have helped push up patent filing activity, industry interest has not grown accordingly; some explanations for this are provided in Section 4.

3.3. Performing pilot and (commercial) demonstration RD & D activities

The step from ideas or models towards real world application of technologies requires testing and demonstration of devices or installations at increasing levels of scale. Experiments are usually classified as lab, pilot, demonstration or commercial scale.

All of the engineering departments interviewed had been applying their technologies at some scale beyond laboratory experiments. An overview is provided in Table 3. This table is not exhaustive: some interviewees had been involved in up to around 10 larger scale projects; projects included in this table are the ones that were chosen to be discussed in detail during the interviews. Although there is no strict guideline on what size of installation classifies as a pilot or demonstration etc., the International Renewable Energy Agency (IRENA) has suggested a classification of production facilities of liquid fuels (Table 4). The interviewees consistently referred to the installations in Table 3 as either pilot or demonstration activities, whilst comparison with IRENA classes indicates that the large majority of these installations could be considered to be of a more advanced development phase.

Table 2
Patents and licensing at China's research institutes and universities.
Source: [58].

Research Institutes						
	Applications filed (2006–2010)				Patents licensed	
	Invention	Utility model	Design	Total	No. (2012)	as% of applications
Top 3	83	146	6	235	54	23.0%
Top 20	1394	578	32	2004	123	6.1%
All (69)	16,078	3409	117	19,604	211	1.1%
Universities						
	Applications filed (2006–2010)				Patents licensed	
	Invention	Utility model	Design	Total	No. (2012)	as% of applications
Top 3	177	7	7	191	11	5.8%
Top 20	9953	1354	300	11,607	181	1.6%
All (116)	103,015	18,515	5715	127,245	635	0.5%

Notes: Data includes 69 research institutes with at least 50 applications between 2006 and 2012: the 116 universities are the top universities as identified in the government's '211 project'. Ranking was based on licensing success, as a share of applications filed.

More surprising than the fact that academics were involved in such large scale production facilities, however, was the extent of their role in such projects. Of course, the research groups contributed their technological knowledge, most often in the form of patented technology, by providing equipment design, and usually also by trouble-shooting and fine-tuning operations. In quite a number of projects, however, their involvement far exceeded this typical academic or engineering role.

For example, the 150 t/a demonstration plant for bio-jetfuel of the Guangzhou Institute of Energy Conversion involved no corporate partner, leaving the organization of construction and operation of the plant entirely to the institute. The demo plant does not market its fuels, but produces batches of fuel of up to circa five tonnes, for testing purposes, including e.g., jet engine tests. Funds for running the plant,

Table 4
IRENA classification of plant scales.
Source: [59]; recalculated from original IRENA classes, which were in volume per annum.

Classification	Production scale	
Pilot	12–20	t/a
Demo	32–400	t/a
Pre-commercial	1–4	kt/a
Commercial	20–40	kt/a
Large commercial	120–200	kt/a

Table 3
Pilot and demonstration activities of interviewed groups.

Group	Technology	Product	Period	Scale	IRENA class
Institute for thermal power engineering, Zhejiang University	Direct combustion with CFB	Electricity	2007 12th FYP	12 MWel 50 MWel	Comm. Comm.
Research Center for Biomass Energy, East China University of Science and Technology	Dilute acid hydrolysis	Cellulosic ethanol	10th FYP	600 t/a	Demo
Biomass Energy Engineering Research Centre, Shanghai Jiao Tong University	Pyrolysis	Producer gas	11th FYP	30 househ.	Pilot
State key laboratory of clean energy utilization, Zhejiang University	Gasification	Producer gas	10th FYP	130 househ.	Demo
College of chemical engineering and material science, Zhejiang University of Technology	Transesterification of UCO	Biodiesel	11th FYP	30 kt/a	Comm.
Faculty of engineering, Zhejiang University	Transesterification of UCO, Castor oil	Biodiesel	12th FYP	150 kt/a	Large comm.
Biomass Energy Research Centre, Guangzhou Institute of Energy Conversion	Sludge incineration	Heat and power	11th FYP	36.5 kt/a	Comm.
Guangzhou Institute of Energy conversion, Chinese Academy of Sciences	Gasification and gas engine	Heat and power	10th FYP	1 MW	Pre-comm.
			11th FYP	5.5 MW	Pre-comm.
	Gasification	DME	2009	100 t/a	Demo
			2010	1 kt/a	Pre-comm.
Guangzhou Institute of Energy Conversion, Chinese Academy of Sciences (coop with others)	Enzymatic or dilute acid hydrolysis	Cellulosic ethanol	2015	4 kt/a	Pre-comm.
Biomass Synthesis fuels and Chemicals Lab, Guangzhou Institute of Energy Conversion	Gasification	Bio-jetfuel	2011	150 t/a	Demo
			12th FYP	1 kt/a	Pre-comm.
		Biogasoline	13th FYP	10 kt/a	Pre-Comm.
Biomass Thermal-chemical Conversion Lab, Guangzhou Institute of Energy Conversion	Fixed bed gasification and gas engine	Heat and power	10th FYP	5 MWel	Pre-comm.
School of Environment, Tsinghua University	Anaerobic digestion of bio-MSW	Biogas	10th FYP	35 kt waste/a	Comm.
Biomass Bio-chemical Conversion Lab, Guangzhou Institute of Energy Conversion	Algae based biodiesel	Biodiesel	2009	10 kt/a	Pre-comm.
			12th FYP	30 kt/a	Comm.
National Key Lab of Biochemical Engineering, Chinese Academy of Sciences	unclear	Cellulosic ethanol	12th FYP	30 kt/a	Comm.
	unclear	Butanol	2012	50 kt/a	Comm.

Notes: Original IRENA classes are for liquid fuels only; classes for power and gas generation are estimates of the authors. Years are provided when it was clear what year production started. Mostly, interviewees referred to periods when the project was planned, constructed or started operation, using reference to Five Year Plan periods. The 10th FYP ran from 2000 to 2005, the 11th FYP from 2006 to 2010 and the 12th FYP from 2011 to 2015.

which is expensive, have so far come from government commissioned research projects, and not from industry.

In the 4 kt/a cellulosic ethanol demo-plant where the Guangzhou Institute for Energy Conversion was involved, there was an industrial partner (a producer of sugar and (fermentation based) ethanol for alcoholic beverages). The project was conceived by the institute and a number of academic partners, however. The industry partner was sought and asked to join only after project funding from the national government had been secured. The project leader indicated that even after project funding had been granted, corporate involvement was not easily secured, and required them to negotiate with several firms before one agreed to cooperate in the project. The industry partner provided the location for the demo plant (on its premises), the fermentation equipment, as well as the feedstock (sugar cane bagasse) free of charge. Contracting an equipment manufacturer capable of providing the pre-treatment equipment, supervision of construction and installation, as well as practical issues such as building and environmental permit applications were the responsibility of the research institutes, however.

Such deep involvement of research groups in demonstration scale projects appeared to be more common in projects that were co-financed by private investors. One problem was that, unlike in the cellulosic ethanol project described above, these investors typically came from entirely unrelated industries. These investors sought to assume the role typical of a venture capitalist, and not that of e.g., a joint venture partner, leaving much more of the organizational aspects to the research groups. As one interviewee commented:

“They have only money; they are an investor. [...] Sometimes I think I work like an organizer of everything. [...] So we should find the manufacturer for different machines by ourselves. And for construction, even; I have to [supervise] their schedule [so that] when the equipment arrives, we have somewhere to put it.”

This comment was echoed by another research group leader, which similarly stated they were responsible for coordination of construction, permit procedures, run-in of the plant, and training of the operators.

Despite the fact that many of the production facilities in Table 3 were at or close to commercial scale, very few have been replicated throughout the rest of China by the industry partners in the projects. Exceptions are the two technologies produced under license, dealt with in Section 3.2. A further example of replication is the gasifiers from the Biomass Energy Research Centre in Guangzhou, which were marketed through a company created by the institute itself (see Section 3.4, on firm creation). The limited replication of projects may, in part, be due to timing; many of these plants have been constructed relatively recently. Other explanations of limited industry involvement and interest in replication are dealt with in Section 4.

3.4. Establishing new firms and production facilities

As for production facilities, there is arguably some overlap with the near-commercial and commercial scale production facilities of fuels and power introduced in Table 3 in the previous section. Apart from these, two clear examples of firms created by research groups came up during our interviews.

First, the Biomass Energy Research Centre of the Guangzhou Institute of Energy Conversion developed a biomass gasifier that can be coupled to a gas engine for the supply of power and heat. The institute established a joint venture together with an industry partner to develop or operate small scale power plants. Throughout the 10th and 11th FYP periods (1996–2005), this company developed approximately 20 projects of around 1 MW_{el} each, and one project of 5 MW_{el}. The projects were located mostly in China, but also in a number of South-East Asian countries. Although the technology performed well, the renewable energy law and subsequent feed-in-tariffs promulgated in China from 2005 onwards, favoured larger scale (30–50 MW) power plants (see also [16]). At these scales, direct combustion technologies are more

financially competitive, leaving little market opportunities for these gasifier units. The Joint Venture partner agreed to buy out the research group, and hasn't managed to expand operations since.

Secondly, researchers at the Biomass Synthesis fuels and Chemicals Lab, Guangzhou Institute of Energy Conversion are currently negotiating plans with a private investor for the construction of a commercial demonstration plant for the production of bio-gasoline, with a capacity of circa 10 kt/a. Although many details were yet to be worked out, the head of the research group leader expected that they would eventually form a joint venture. He further indicated that this would be at the investors' request. As the technology had not been used at this scale before, the investor would want to ensure a strong commitment from the institute to ensure smooth run-in and operation of the plant, and considered that a direct financial stake in the project would be the best incentive to ensure such commitment.

4. Limits to academic entrepreneurship in driving development of China's advanced bio-energy technology sector

Section 3 revealed that within the Chinese academic community working on advanced bio-energy technologies, there are plenty of examples very entrepreneurially minded research groups. These activities have so far not resulted in wide-spread diffusion of these advanced bio-energy technologies in China, however. Below we describe five reasons why these technologies have seen limited commercialization, despite strong academic entrepreneurship.

4.1. Industry demands highly mature technologies

First, industry appeared to have very high expectations on the maturity of technologies produced by academic organizations, and has been reluctant to be strongly involved in technological development processes.

For example, the development of the commercially successful CFB biomass boiler by the institute of thermal power engineering at Zhejiang University, had very little industry involvement. Even after successful demonstration of their 12 MW boilers, the development of the second generation, 50 MW, boilers had depended entirely on financing from government research funding, and some investment from the institute itself.

The researcher that coordinated the 4kt/a cellulosic ethanol demonstration by the Guangzhou Institute of Energy Conversion (see also Section 3.3) stated that they were not concerned that equipment manufacturers, contracted to manufacture the pre-treatment reactor, would pirate or sell on the technology. She argued that, as the technology was only in the demonstration phase, the technology, and the patent, did not have much commercial value just yet. Firms would only be interested in licensing or buying the technology if and when it would be financially competitive. Nearly all our interviewees echoed this argument as a reason why industry interest for their technologies had been lacking.

Novel technologies, however, seldom come out of the laboratory ready for wide-spread market roll out. There is a role for entrepreneurs to select promising technologies and develop these towards marketable solutions, either unilaterally or in co-operation with academic partners. The Chinese energy industry, then, appears to have a somewhat short-term view on profitability, and their reluctance to participate in the further development of these technologies suggests a limited entrepreneurial spirit in industry rather than academia. The fact that a small number of private investors with limited or no background in petrochemical or power sectors are venturing into this strongly government controlled industry further indicates that the state owned energy companies in particular are unwilling or reluctant to invest in these advanced biomass technologies, which still have a somewhat longer timeframe to profitability.

This passive stance towards this sector of these SOE is somewhat

surprising, as the Chinese government has managed to ensure strong participation of SOE in the development of other renewable energy sectors. These have, for example, been actively involved in the development of a domestic wind turbine manufacturing sector [60–62]. A number of SOE have further been active in first generation (i.e., grain based) fuel ethanol production [17] (see also Section 4.5). There are a number of reasons that differentiate advanced biomass energy technologies from these other examples, some of which reflect more limited government guidance. These include (1) more limited market creation policy (more in Section 4.3); (2) a preference of developers for larger scale projects, which are more difficult when crop residues need to be sourced within a relatively small area around a project [16]; (3) difficulties in sourcing a secure supply of biomass residues at relatively stable prices (more in Section 4.4); (4) more limited potential for the import and transfer of matured foreign technology (more in Section 4.5); (5) political hesitation for strong support over concerns for land and water shortages in case of increased crop cultivation for energy purposes [17,18]; and (6) the fact that biomass energy policy is the domain of MOA rather than the NDRC, which issues policy for other (renewable) energy sectors and has far greater political power [63,64]. Industrial development and catching-up policies for the wind power sector have been far more elaborate and coherent for the wind power than for the biomass energy sector [62].

4.2. Industry demands very large scale demonstration of technologies

Related to the previous point; the potential industry partners for advanced bio-energy technologies demand a very large scale of demonstration performed by research organizations, before they join development efforts. This is most clear from the comparison of demonstration plant sizes with IRENA classifications plant sizes. One of our interviewees had work experience in Germany and Canada, and indicated that research groups in China tended to be involved in larger scale plants, or “have to go further along the innovation chain” than his previous colleagues would have. He argued that industry in those countries would have approached research institutes for more fundamental research questions, whereas the Chinese industry would only start to get interested when processes had been proven at scale. He also argued that the Chinese government too, more strongly encouraged the involvement of academic personnel in larger scale facilities with its research funding. This was not necessarily a complaint, as he agreed it was the role of engineers to put technologies into practice. Others did complain. The following quote from one researcher was representative of comments by a number of others:

“We don’t have the ability, the power, to make these things. We can resolve some technological problems, but we cannot make these products for commercialization to be used, not [at] this large scale.”

The lack of industry involvement is not only a problem because research groups or their research grants have limited financial capacity. Actors from industry are likely better placed to deal with such issues as the construction and operation of a larger scale plant, sourcing the required feedstock and marketing their product, dealing with regulatory issues and lobbying for necessary or more beneficial policy for advanced bio-energy markets, etc. The existence of a number of large scale demonstration plants, largely organized by academic organizations, indicates that these have been able to make up for the lack of industry involvement to some extent. Further scale-up or wide-spread replication of such plants, however, seems unlikely without substantial industry involvement.

4.3. Market creation policies are deficient

Interviewees working on liquid biofuels in particular argued there were deficiencies in policy for market creation. For fuel ethanol, there has been a mandatory use of 10% ethanol blends in a number of

provinces and cities, a subsidy for every ton of fuel produced, as well as a guaranteed minimum level of profit for each producer of fuel (for more details see also [17]). Market entry into fuel ethanol production is strongly restricted, however. Approval for such production has so far been awarded to state owned enterprises (SOE) only. These are not necessarily energy sector SOEs; COFCO, the country’s largest grain processor, is involved in a number of ethanol plants. In the 4kt/a cellulosic ethanol demonstration by the Guangzhou Institute of Energy Conversion (see Section 3.3), a state owned sugar factory is involved. Restrictions were motivated over a concern of competition between food and fuel uses with first generation fuel ethanol. One of our interviewees claimed that second generation ethanol production remained restricted over fuel quality concerns, whereas another indicated government may fear mislabelling of first generation fuels as cellulosic ethanol in a less controlled sector. The current high levels of oversight on flows of feedstocks, for example, has enabled government to issue quota on the use of sugar, of which there is a current surplus in Chinese markets, for ethanol production. There are no restrictions to market entry for biodiesel, but also no support policies in terms of mandated use or subsidies. As a consequence, the biodiesel market is far smaller [17].

Researchers working on bio-gasoline projects saw great obstacles in marketing their fuel. There is no fuel standard, no production subsidy, and fuel retailers cannot use bio-gasoline blending to fulfil ethanol blending obligations. In discussions on possible future policy, government officials argued the sector needed to achieve some scale before such instruments would be implemented, essentially causing a stalemate as researchers argued there would be no further scaling without sufficient market creation policy. One interviewee also argued this had been less of a problem in early ethanol fuel production as large scale ethanol production capacity already existed for different products and could readily be repurposed for fuel production.

4.4. Energy and biomass feedstock prices are very volatile

Fossil fuel prices, in particular those of oil, but those of coal and natural gas as well, have been very volatile over the past decade. It is therefore difficult for investors to forecast at what levels of production costs of biomass-based transport fuels or power generation, these will be able to compete with fossil alternatives. There is further uncertainty and risks from strong rises in biomass feedstock prices witnessed in areas surrounding biomass energy projects [cf. 16,18]. One interviewee stated that they sought to establish cooperation for demo and commercial plants only with companies with control over feedstock, such as rice or sugar cane mills. Outside of such niches, however, the volatility of energy and biomass feedstock prices can be expected to lead to reduced investor interest in the advanced bio-energy technologies provided by research organizations.

4.5. Competition with foreign technology suppliers

The quality of energy conversion technologies, including in such aspects as efficiency, maintenance needs, and in some cases energy consumption, affects profitability and therefore investor interest. It is very difficult, and well beyond the scope of this paper, to compare the quality of domestic versus foreign biomass energy technologies. Many of our interviewees did indicate that competition with foreign technology providers made it more difficult for them to market their products, however. This is visible in a number of market segments. China’s first large scale cellulosic ethanol plant, for instance, was a cooperation between COFCO and Novozymes, a global market leader in enzymes for biofuel production [17]. In biomass power generation, the market was dominated by a joint venture (DP Cleantech) between a Danish technology provider and a Chinese developer and operator, in the years immediately following the creation of a feed-in-tariff for biomass power in China [16]. Technological quality and track record are likely to have

played a role in the choice for foreign over domestic technology, but two interviewees also stated that Chinese project developers, especially in first tier cities, were inclined to use foreign technology as it would give a more modern or advanced appearance to their projects.

Foreign technology has also played a key role in the development of the Chinese wind and PV sectors [62]. The dominant technology transfer mechanism in the early phases of the Chinese wind turbine manufacturing sector was licensing of foreign turbine designs, followed by mergers & acquisitions, cooperative development and independent development as technological capacities in the sector grew. Similarly, domestic manufacturing started out with less complex components such as towers and foundations, later followed by generators, gearboxes, blades, inverters and control systems, as domestic technological capacities progressed [60,65,66]. A prominent domestic research institute, the Institute of Wind Energy at the Shenyang University of Technology (SUT), managed to commercialize its technology through the creation of a spin-off company (China Creative). It has had more difficulties licensing its designs, finding demand mostly from lower tier manufacturers with very little turbine sales [61].

Arguably, there is less potential for technology transfer in advanced biomass energy technologies, as the availability of foreign technology that is ready for roll-out is limited. Most second generation biofuel projects, globally, are still in the pilot and demonstration phase [67,68]. For example, these technologies make up 13 out of 39 projects funded through the EU's NER 300 program (running from 2014 to 2020), an innovation fund for demonstration of novel renewable energy technologies [69].

5. Conclusion and policy implications

Developments in China's advanced bio-energy sector are slow, and are behind on policy targets even though these were only of limited ambition levels. A lack of academic entrepreneurship, often identified as a barrier in early commercialization stages of novel technologies, does not appear to be a root cause here, however. Academia in this sector appear very entrepreneurial: they consider the future commercial potential of different technological pathways when deciding on research priorities, they patent and attempt to license their technologies, they are highly involved in very large scale demonstration plants and have in some cases managed to create new firms or production facilities.

A bigger barrier to further development of the nascent sector appears to be the unrealistic expectations from both industry and government on the level of maturity and scale of technologies that come out of the academic research system. Industry seems reluctant to invest before the technologies have been demonstrated at (even) larger scale, have sufficient track record, and have clear market opportunities, whilst government seems reluctant to develop market creation policies until the technologies have better financial performance. This has created somewhat of a stalemate. Seen the current status of many of the technologies analysed here, academics have exhausted much of their potential to contribute to maturation of these technologies unilaterally (in terms of scale and financial performance), and further maturation will depend on stronger industry involvement, and market creation by policy.

Breaking this stalemate requires policy makers to create better market access and a clearer market value for these technological pathways, in a bid to attract investor interest. This could be in the form of subsidies that apply to every litre of biofuel, rather than being limited to fuel from the small number of first generation ethanol plants operated by SOE. This does not necessarily have to be a level of subsidy where production of such fuels is profitable at current performance levels. Any level is better than none, as it at least creates a price point for academia and industry to work towards with further technological development. It is, in fact, somewhat surprising that this has not occurred, as China has had good experiences with supporting renewable

power generation with feed-in-tariffs [62]. Transport fuels are also subject to strong pricing regulation. Recently, China even introduced minimum retail prices for (fossil) gasoline and diesel, in a bid to protect oil companies from some of the fluctuations in international crude oil prices [70]. A number of bio-fuels lack market value altogether: even the price level of fossil fuel alternatives is irrelevant as a number of bio-fuels cannot be produced by certain actors and/or be marketed at all. Market access and value could also be created by allowing blending mandates to be fulfilled with any bio-fuel, rather than limiting it to ethanol fuels only. This would allow fuel distributors to compare bio-fuel prices and seek the most economical way to fulfil their mandates, whilst simultaneously creating a development perspective for a wide variety of biofuels.

Limiting fuel distribution and ethanol fuel production to large state owned enterprises limits the diversity of actors involved in the innovation system for biofuels. This reduces competition and the pressure to innovate, in particular as our interviews revealed that a number of private enterprises were interested in experimenting with biofuel production and sales. China's policy makers do have more influence over the corporate strategy of SOE than over that of private enterprises, however, and this influence, too, could be used to steer more investment towards developing a wider range of bio-fuels. Again, encouraging such investment behaviour would be easier if these fuels also had a clearer market value.

It is further advisable to reconsider the focus on patent numbers in evaluation criteria from academic institutions and government research funds. Stimulus or obligation to produce patents has inflated patent applications, and created significant side-effects. Academia are spending time and effort producing patents of little worth for the sake of meeting evaluation demands, patenting bureaus are spending resources processing these applications, and government funds are used to create inflated statistics rather than useful research results.

Results presented here provide some contrast with existing literature on academic entrepreneurialism and the 'third mission' of universities. First, in contrast with a common critique in the literature on academic entrepreneurialism, our results highlight that academic personnel can have both entrepreneurial mind sets and skills. Second, our results highlight that limited commercialization of novel technologies is not always due to lacking academic entrepreneurialism. As pointed out by the 'Technological Innovation Systems' framework (section 2), such commercialization requires active participation by a wide variety of actors. Much previous work has focused on (quantitative) analyses of output from academic organizations in terms of e.g., patents, licensing agreements, start-ups, industry collaboration, etc., and how such output could be improved through e.g., policies that mitigate legal or organizational barriers to commercialization at academic organizations [e.g.,50,51,52]. Our case study highlights that many types of outputs depend just as much on industry demand and demand creation through policy. It is therefore too simplistic to immediately equate a lack of such output with lacking academic entrepreneurialism.

Lastly, it is important to point out that the strong domination of State-Owned Enterprises and the very high level of government regulation of the (biomass) energy sector in China present a fairly unique environment for the commercialization of novel technologies. These characteristics do not preclude successful sector development, as evidenced by other renewable energy sectors in China, but neither do they necessarily provide strong stimulus for the use of technology developed by domestic academia [62].

Conflicts of interests

The authors declare no conflict of interest. Sponsors mentioned in the acknowledgement did not have any involvement in research design or reporting.

Acknowledgements

We would like to thank SIDA, the Swedish Energy Agency and IVA for financial support. We are grateful for financial support for exchange

visits to China from Zhejiang University under the ‘111’ project. We would like to thank the interviewees, listed in [Appendix A](#), for their time and effort in supporting our analysis.

Appendix A. List of interviewees

#	Affiliation	Research area
Academics in engineering fields		
1	Institute for Thermal Power Engineering – Zhejiang University	Direct combustion (CFB boilers)
2	Department of Chemical Engineering for Energy Resources – East China University of Science and Technology	Bioethanol
3	Research Center for Biomass Energy – East China University of Science and Technology	Bioethanol
4	State key laboratory of clean energy utilization – Zhejiang University	Biomass gasification
5	Zhejiang province key laboratory of bio-fuel technology – Zhejiang University of Technology	Biodiesel
6	Zhejiang Province Key Laboratory of bio-fuel technology – Zhejiang University of Technology	Biodiesel
7	Zhejiang Province Key Laboratory of bio-fuel technology – Zhejiang University of Technology	Biodiesel
8	Institute for Thermal Power Engineering – Zhejiang University	Sewage sludge incineration
9	Bio-chemical Conversion Lab – Guangzhou Institute of Energy Conversion – CAS	Bioethanol
10	Biomass Energy Research Centre – Guangzhou Institute of Energy Conversion – CAS	Combustion and gasification
11	Biomass Energy Research Centre – Guangzhou Institute of Energy Conversion – CAS	Bioethanol
12	Biomass Energy Research Centre – Guangzhou Institute of Energy Conversion – CAS	Bio-DME, jet fuels, biogasoline
13	Biomass Thermal-chemical Conversion Lab – Guangzhou Institute of Energy Conversion – CAS	Fixed bed gasification
14	Department of Environmental Science & Engineering – Tsinghua University	Sludge incineration and anaerobic digestion
15	Key Laboratory of Renewable Energy – Guangzhou Institute of Energy Conversion – CAS	Biodiesel
16	Guangzhou Institute of Energy Conversion – CAS	Algae oil
17	National key lab of Biochemical Engineering – Institute of Process Engineering – CAS	Cellulosic ethanol
18	Department of Microbiology and Immunology – China Agricultural University	Cellulosic ethanol
19	College of Agronomy and Biotechnology – China Agricultural University	Cellulosic ethanol
20	Biomass Engineering Center – China Agricultural University	Biogas, policy/strategic research
21	Biomass Energy Engineering Research Centre – Shanghai Jiaotong University	Biogas, ethanol, pyrolysis and biodiesel
Academics in non-engineering fields, policy and industry experts		
22	School of Environment – Tsinghua University	Policy (university)
23	Energy Strategy Research Center, Guangzhou Institute of Energy Conversion – CAS	Policy (research institute)
24	Energy Strategy Research Center, Guangzhou Institute of Energy Conversion – CAS	Policy (research institute)
25	CREIA – Chinese Renewable Energy Industries Association	Policy (industry association)
26	CREIA – Chinese Renewable Energy Industries Association	Policy (industry association)
27	Center for Renewable Energy Development, Energy Research Institute, NDRC	Policy (governmental research institute)
28	Center for Renewable Energy Development, Energy Research Institute, NDRC	Policy (governmental research institute)
29	Local rural energy office, Hangzhou	Biogas
30	Local rural energy office, Hangzhou	Biogas

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